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SATELLITE RELAYING OF GEOPHYSICAL DATA

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GREENBELT, MARYLAND

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ABSTRACT

Data Collection Platforms (DCPs) for transmitting surface data to an orbiting satellite for relaying to a central data distribution center are being used in a number of geophysical applications. "Off-the-shelf" DCP's, transmitting through Landsat or GOES satellites, are fully capable of relaying data from low-data-rate instruments, such as tiltmeters or tide gauges. In cooperation with the Lamont-Doherty Geological Observatory, Goddard has successfully installed DCP systems on a tide gauge and tiltmeter array on Anegada, British Virgin Islands.

Because of the high-data-rate requirements, a practical relay system capable of handling seismic information is not yet available. However, the necessary components are developed or are well along in development and we hope to have an operational prototype system within the next year. Such a system could become the basis of an operational hazard prediction system for reducing losses due to major natural catastrophies such as earthquakes, volcanic eruptions, landslides or tsunamis.

CONTENTS

	<u>Page</u>
INTRODUCTION	1
ADVANTAGES OF A GEOPHYSICAL SATELLITE RELAY SYSTEM	3
SATELLITE COLLECTION OF ANEGADA GEOPHYSICAL DATA	5
DEVELOPMENT OF SEISMIC DCP	6
1. Seismic Event Detector	7
2. Event Storage	9
3. Data Compression	10
4. Satellite System	11
REFERENCES	12

ILLUSTRATIONS

<u>Figure</u>	<u>Page</u>
1 Block Diagram of a Typical Satellite Data Relay System . . .	15
2 Major Scientific and Engineering Disciplines now using Satellite Data Collection and Relaying Systems	16
3 Anegada, B. V. I., Tide Gauge DCP Satellite Data Relay Installation	17
4 Anegada Tide Gauge DCP Antenna Installation	18
5 Geophysical Parameters Contributing to Studies on Crustal Hazards	19
6 Block Diagram of a Seismic Data Collection Platform	20
7 Capability of Automatic Seismic Event Detection as a Function of Scientific Usefulness	21

SATELLITE RELAYING OF GEOPHYSICAL DATA

INTRODUCTION

This report describes the "state-of-the-art" in ground and spacecraft instrumentation for near-real-time satellite relaying of remote data, analyzes the advantages of this data collection method for field geophysics, describes a Goddard/Lamont low-data-rate relay system operating on Anegada, B.V.I., and discusses present Goddard plans to upgrade the system to include collection of seismic data for crustal hazard monitoring. Figure 1 illustrates the basic components of a typical system. The most variable element, the sensor, is not limited to geophysical data but can be used to collect information in such diverse fields as ecology, agriculture or search and rescue operations (Figure 2). A signal conditioner which matches the sensor output to the Data Collection Platform (DCP) input, or a field microcomputer programmed to extract specific information or compact the data stream before transmission by the DCP, may be required for specific applications. The DCP times the entire system, collects identification and housekeeping data, and prepares and transmits this information to the orbiting satellite. The Data Collection Center identifies the data from the individual sensors, reduces it to the form requested by the users, and forwards it to the user in the fastest possible time (often less than one day after receipt).

Data Collection by satellite is a relatively new technique first demonstrated in 1967 using NASA's ATS-1 (Applications Technology Satellite) satellite. The

first demonstration was the NASA Omega Position Location Equipment System (OPLE) which proved that accurate positions could be obtained from platforms in remote locations and that a satellite relay did not degrade the data. This experiment was followed in 1969 by the Interrogation, Recording and Location System (IRLS) flown on Nimbus 3 and Nimbus 4. This was the first global satellite system to demonstrate the worldwide capabilities of satellite data collection. The IRLS concept was also applied to the French EOLE satellite launched in 1971.

These ground systems, because they were designed to respond to interrogations from the satellites, were relatively large and expensive, and required considerable power. This was overcome in the Landsat series of satellites, initiated in 1972, by designing the ground platforms to transmit at random times, thus eliminating the requirement for having a receiving system in the DCP.

A major geophysical program using the Landsat satellite was the USGS prototype volcano surveillance system on 15 volcanoes in Alaska, Hawaii, the contiguous United States, Central America and Iceland (Ward, et al. 1974). While the locations and DCP's have been modified, the basic system is still in operation furnishing information on the number of earthquakes per day and ground tilt in the neighborhood of the monitored volcanoes.

In 1974 NOAA introduced the GOES (Geostationary Operational Environmental Satellite) satellite system which employed either a scheduled or satellite interrogated transmission system. Costs were kept low because of semiconductor

technology improvements. In 1978 the French plan to initiate the ARGOS Location and Data Collection System using Tiros N and NOAA A and a random DCP transmission system. These spacecraft will be in quasi-polar orbit and provide world coverage. Relay systems existing on commercial domestic or international satellites have not, as yet, been used for systematic relaying of sensor data. However, Comsat General Corporation and the Water Resources Division of the U.S. Geological Survey initiated an evaluation program in October of 1977 for relaying data on stream levels and water quality through the Telesat Canada synchronous satellite ANIK-1 (Aviation Week and Space Technology, 1977).

ADVANTAGES OF A GEOPHYSICAL SATELLITE RELAY SYSTEM

Conventional field systems, particularly seismic, either have to be visited every day or two, to replace the chart paper, or the information has to be transmitted to a central location via expensive and sometime noisy phone lines and/or radio relays. Phone lines, almost non-existent in remote or underdeveloped seismic areas such as Alaska, are often unreliable, even in populated areas. Furthermore, ground communications generally become inoperative before, during, and after a major earthquake. When geophysical systems are operated in extremely inaccessible regions, data are usually preserved on low-powered, slow speed recording systems which can run unattended for months; the data are then collected several times a year. Such systems require sacrifices in timing accuracy and information content, and, since data analysis must be delayed for months after the events, earthquake prediction capability is lost. Also, there

can be no assurance that the instrument is performing as planned. In addition, it is often essential to augment rapidly a seismic network to collect earthquake precursor signals or monitor aftershocks, and the dependence upon phone lines or radio relays seriously impedes the mobility of instrument siting and increases installation time.

Early in the development of Data Collection systems it was obvious that, to achieve general acceptance, the cost of the units must be kept low. The decreasing cost of microprocessor technology has helped achieve this goal. DCP's transmitting on either random (Landsat) or fixed (GOES) time schedules are now around \$3,500.00 apiece. If a receiver is included in the DCP, enabling it to respond to satellite interrogation (GOES), the prices are in the \$5,000.00 neighborhood. As long as the initial cost of the satellite is not included, it appears that the cost of a satellite system is competitive with phone lines and radio relays, particularly if low cost government leased phone lines are not available. Studies now underway should establish the practicality of private firms leasing DCP and satellite time to investigators (Forcina and Smalley, 1977).

The greatest value of satellite relaying is, however, the acquisition of real time geophysical data from those isolated and inhospitable regions where no other data retrieval method is possible or feasible. For example, a recent survey conducted by the Regional Seismological Center for South America (CERESIS) indicates that present coverage of seismic events in South America is only complete for earthquakes with magnitude equal or above 4.8. On this one

continent it is estimated that a total of about 2200 seismic events with magnitude between 4.0 and 4.7 take place per year, but present detection capabilities are not sufficient to locate them or even to detect them (Fernandez, 1976). It is apparent that a few, well placed sites could greatly improve this situation but collecting the data in a timely manner by conventional communication methods is a major problem.

SATELLITE COLLECTION OF ANEGADA GEOPHYSICAL DATA

Anegada, British Virgin Islands, is a small island at the northern end of the Lesser Antillian Arc where the chain of Caribbean islands suddenly turns westward. Low seismic activity in comparison with neighboring sections of the arc suggests that this may be a locked seismic zone capable of supplying valuable earthquake precursor data. For this reason the Lamont-Doherty Geological Observatory of Columbia University (LDGO) is collecting strain, tidal, tilt, leveling and seismic data from this area. Much of these data are collected by resident caretakers and returned to LDGO by mail or courier which imposes undesirable delays in analyzing the data, allows instrument breakdowns to exist for some time before being detected, and does not permit quick reactions to sudden changes in geophysical parameters.

In 1976 Goddard engaged in a joint project with Roger Bilham of LDGO to demonstrate the feasibility of collecting low-data-rate geophysical information using the Landsat satellite relay system. Figure 3 shows the initial installation on one of the tide gauges using an interface designed and made by LDGO and

Goddard. On the left is a voltage controlled oscillator feeding into the interface box (background) and then into a General Electric DCP (foreground). Power was supplied by gel-cell batteries with one-year lifetimes. The data were transmitted to the spacecraft by a small, printed-circuit, helix antenna (Figure 4). Each transmission consisted of 8 data sets, with each set representing 1-1/2 hours of integrated and averaged tide data. Data were relayed 6 to 8 times a day when the orbiting Landsat was in mutual view of Anegada and Goddard. The system performed satisfactorily for over a year until the batteries failed.

Goddard has recently completed the design and construction of a more advanced interface that utilizes two LaBarge DCP's to relay the data from six tiltmeters (Allen, W. K., et al. 1977). This interface, which is more rugged, requires less power and is smaller than the original tide gauge DCP, was installed on Anegada in September, 1977 and is returning excellent data.

DEVELOPMENT OF SEISMIC DCP

In contrast with the ready availability of the low data rate assemblages already discussed, no practical relay system exists for satisfactorily returning seismic data because of the high data rates involved. It will be no problem on such a system to "piggy-back" information from low data rate instruments. This type system, in view of its major advantages of ease of installation, particularly in areas with little or no existing communication facilities, and the near-real-time availability of the data, appears particularly suited for crustal hazard studies and, eventually, an operational hazard prediction system for

reducing losses due to major catastrophes such as earthquakes, volcanic eruptions, landslides or tsunamis. Goddard, in cooperation with the USGS, should have a completed prototype of this system by the fall of 1977.

The geophysical parameters involved in crustal hazard studies are listed in Figure 5. Seismic information is obviously of major importance to these studies. Details on the requirements are contained in a 1975 NASA study (Wolff et al. 1975). Figure 6 is a block diagram of the proposed Goddard system. The critical components are discussed below.

1. Seismic Event Detector

The most straightforward way of reducing seismic data requirements is a device that will reliably identify and preserve seismic events while discarding background noise. Such a device could reduce on-site recording time from 24 hours a day to probably less than one. The majority of devices for accomplishing this have generally depended on a manually set threshold for comparing short term energy (signal) with long term energy (noise). The reliability of such a device is considerably increased when cross correlation between multiple seismic stations is possible (Morris, 1973; Lane, 1974). This cross correlation is obviously not feasible when a single seismometer/DCP system is under consideration.

Omote et al. (1955, 1957) developed a single channel energy level triggering scheme for preserving paper and chemicals while recording at a fast record

speed. A revolving endless magnetic tape loop served as a delay line enabling a reproducing head to record and preserve the start of an event when activated by an event detector that was triggered when the input energy exceeded a selected pre-set level. The percentages of "false picks" or "not recorded" events was critically dependent on the adjustment of the energy level required to trigger the system. Aki et al. (1969) utilized a similar system for recording microaftershocks on the Kenai Peninsula in Alaska. Stewart et al. (1971; 1977) developed a system of monitoring up to 32 channels of data and detecting local earthquakes in real time. Their algorithms, designed for relatively impulsive events, filtered out low frequency components, successfully eliminated transient events and automatically compensated for variations in long term noise level. Onset times, determined automatically, are in good agreement with "hand" picks. A scheme similar to Stewart's was employed by Stevenson (1976) to detect microearthquakes at Flathead Lake, Montana. In this case, two passes were made through the data; the first pass identifying the event and the second pass timing the onset.

Ambuter and Solomov (1974) developed an ocean bottom event picker/magnetic tape recorder. Their event detector utilized short term and long term averages to survey the background noise, set a threshold and trigger a recorder. Crampin and Fyfe (1974) describe a computer controlled tape searching system with three separate sampling rates to eliminate transients and detect local, regional or teleseismic events.

Recent efforts are concerned with generating increased confidence in the automatic functions of the computer program. Allen (1977) is producing a system, expressly designed for inexpensive low-power microprocessors, that will record arrival time, direction of first motion, apparent "size" at the station, describe the event in frequency and amplitude and furnish a reliability number for the pick. Joint efforts by the USGS and NOAA have developed an event picker that utilizes frequency, amplitude and duration to decide on an event (Clark, 1975; Clark and Medina, 1976). In this case the P wave arrival times of the last four events are stored and relayed via the GOES satellite to a central station. Advanced detection schemes under consideration include better frequency discrimination utilizing a fast Fourier transform designed for microprocessors (Tenn., Univ. of, 1976) and the use of Artificial Intelligence to program a computer to analyze the data stream as would a seismologist (Anderson, 1976).

2. Event Storage

Continuously recording seismic data, using an 8-bit word for signal device and sampling at 60 Hertz, requires over 40 megabits per day per seismic axis. If an event detector is employed and each event is recorded for a maximum of 2 minutes (10 seconds pre-event noise and 110 seconds of event), and the sampling rate is reduced to 40 Hertz, then each event would consist of about 40 kilobits per axis. A storage system of 400 kilobits (50,000 eight-bit words) would then permit 10 events to be stored between transmissions. If the system "dumped"

once a day this would provide a capability of ten events per day, which should be sufficient for recording most normal daily seismic activity unless swarms occur. While magnetic tape can easily store this amount of data, mechanical motion poses problems in long term reliability and fieldworthiness. Magnetic bubble memories or CCD's (Charge Coupled Devices), while still in the developmental stage, offer attractive alternatives and are being investigated.

3. Data Compression

While the above seismic data rate can be accommodated by present synchronous satellites, such a data rate is not desirable if many seismometers are reporting through the same system. Therefore, further data compression of the picked events is needed. The overall extent of compression is the limiting factor in the number of seismometers a given relay system can accommodate.

Figure 7 relates data that could be automatically picked in the field with its scientific utility. Existing microcomputers can be programmed with minimum difficulty to furnish all of the information listed in the Figure except the time of the S wave arrival. The problem here is the difficulty of computer identification of the S wave for a complex event. Until seismologists have more confidence in automatic seismic processing, even if the S wave can be picked reliably by a computer, it appears likely they will require the return of an accurate analogue record so they can perform their own analysis and verify the automatic picking results. The problem is, then, to reduce the data requirements for the analogue record by applying compression or compaction before the data are transmitted

from the DCP. Simple compression schemes, such as transmitting only time and amplitude of turning and inflection points, appear to preserve nearly all the original information. Other studies have considerably more complex transforms (Wood, 1974), but further investigations are needed to determine how much compression is possible before a permanent loss of significant data occurs. The other components shown in Figure 6 are standard "off-the-shelf" equipment and need not be discussed here.

4. Satellite System

The two existing satellite systems now extensively engaged in data relaying are the Landsat (formerly called ERTS) operated by NASA and the GOES (Geostationary Operational Environmental Satellite) operated by NOAA. The Landsats (1, 2 and C) employ a 401.55 MHz uplink frequency and a 64-bit total message block composed of 8 bytes (i.e., eight 8-bit measurements can be transmitted in one message). These satellites have a nearly circular 900 km orbit and a 100 minute orbital period. At least one message can be relayed at each overhead pass of the spacecraft, with the maximum number of messages being 7 and the typical number 2. The minimum number of visible passes per day is 2, the maximum 6, and the typical 3. Transmission rate is 5 kilobits per second, and transmission intervals, set at the DCP, are either 3 minutes or 90 seconds.

Increased data handling capability is furnished by the GOES (1, 2; SMS 1, 2) synchronous satellites. This spacecraft employs a 401.7 MHz uplink frequency and has a maximum data block length of 2 kb. At the typical installation, DCP

self-timed transmission occurs once every 3 hours. Transmission rate is 100 bps. The use of an entire GOES channel permits transmission at the 100 bps rate as long as necessary, assuming proper framing. This system also has a command capability which allows individual DCP's to be turned on by the satellite.

The primary ground control and data distribution center for Landsat is at Goddard Space Flight Center, Greenbelt, Maryland. Other stations capable of receiving Landsat relayed data are at Goldstone, California and Fairbanks, Alaska. GOES data is received at Wallops Island, Va., and ground linked to Suitland, Md. for distribution.

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FIGURE CAPTIONS

Figure 1. Block diagram of a typical satellite data relay system.

Figure 2. Major scientific and engineering disciplines now using satellite data collection and relaying systems.

Figure 3. Anegada, B. V. I., tide gauge DCP satellite data relay installation.

Figure 4. Anegada tide gauge DCP antenna installation.

Figure 5. Geophysical parameters contributing to studies on crustal hazards.

Figure 6. Block diagram of a seismic data collection platform.

Figure 7. Capability of automatic seismic event detection as a function of scientific usefulness.

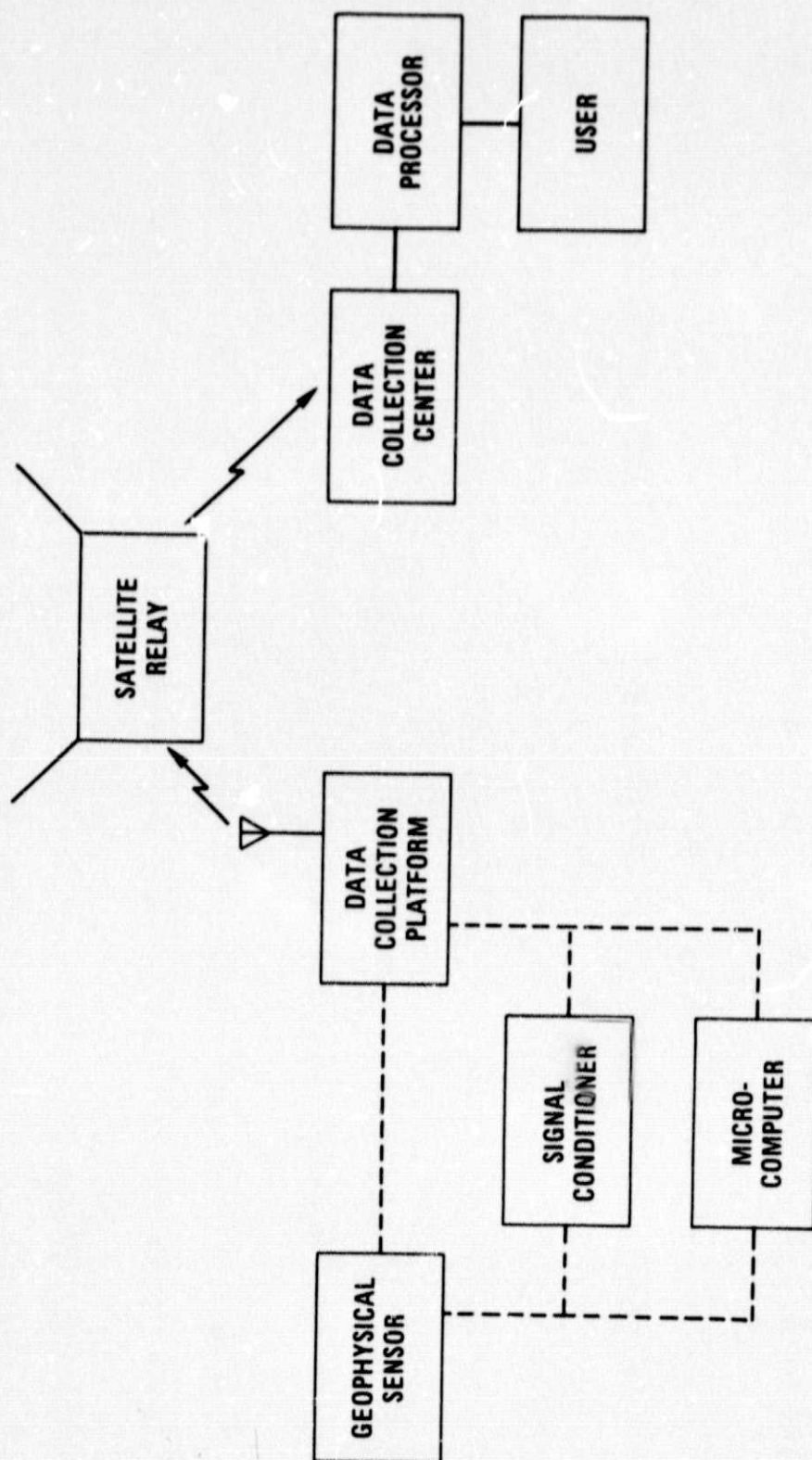


Figure 1. Block Diagram of a Typical Satellite Data Relay System

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AGRICULTURE

METEOROLOGY

BIOLOGICAL BEHAVIOR

NAVIGATION

ECOLOGY

OCEANOGRAPHY

GEOPHYSICS

SEARCH AND RESCUE

GEOLOGY

TRANSPORTATION

HYDROLOGY

Figure 2. Major Scientific and Engineering Disciplines now using
Satellite Data Collection and Relaying Systems

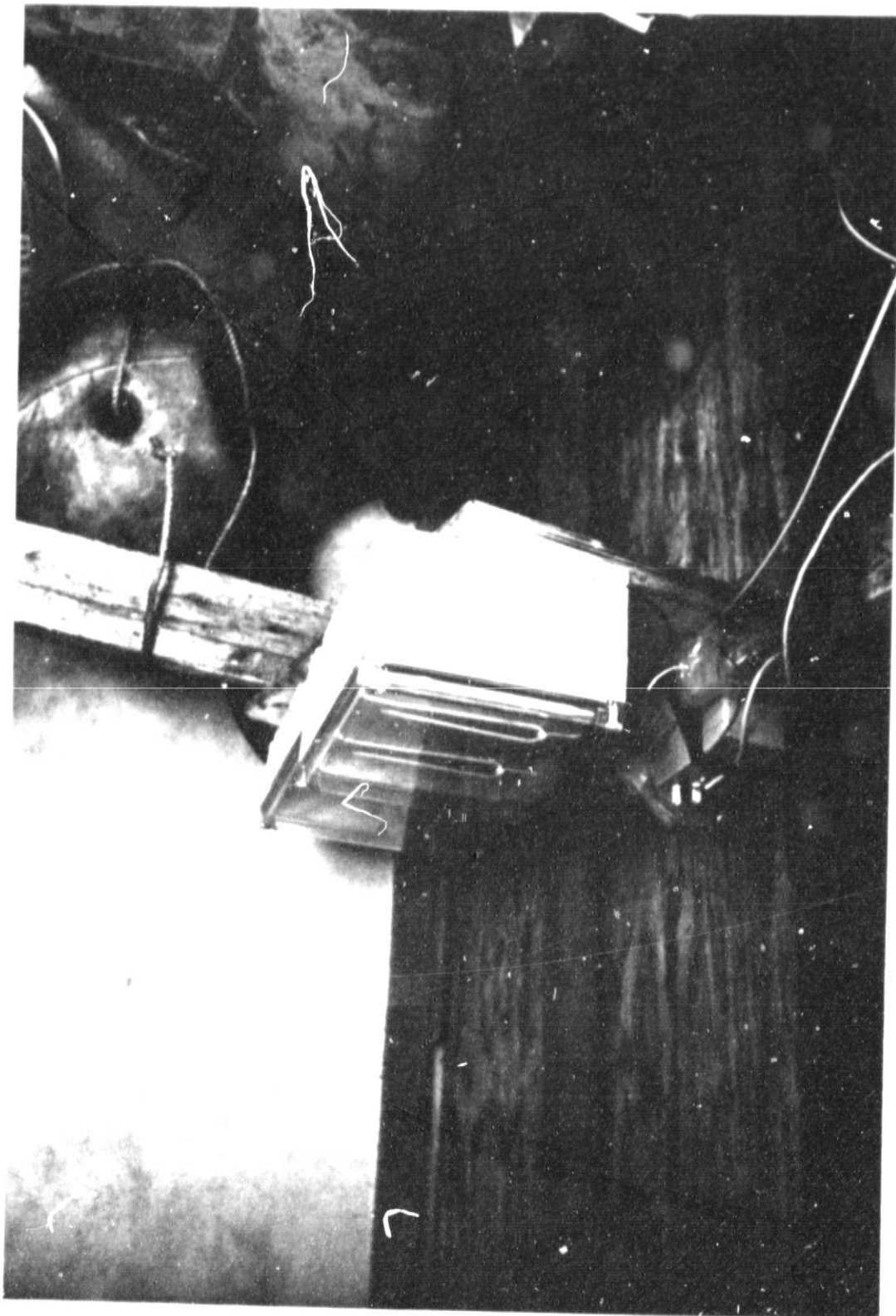


Figure 3. Aneгада, B. V. I., Tide Gauge DCP Satellite Data Relay Installation

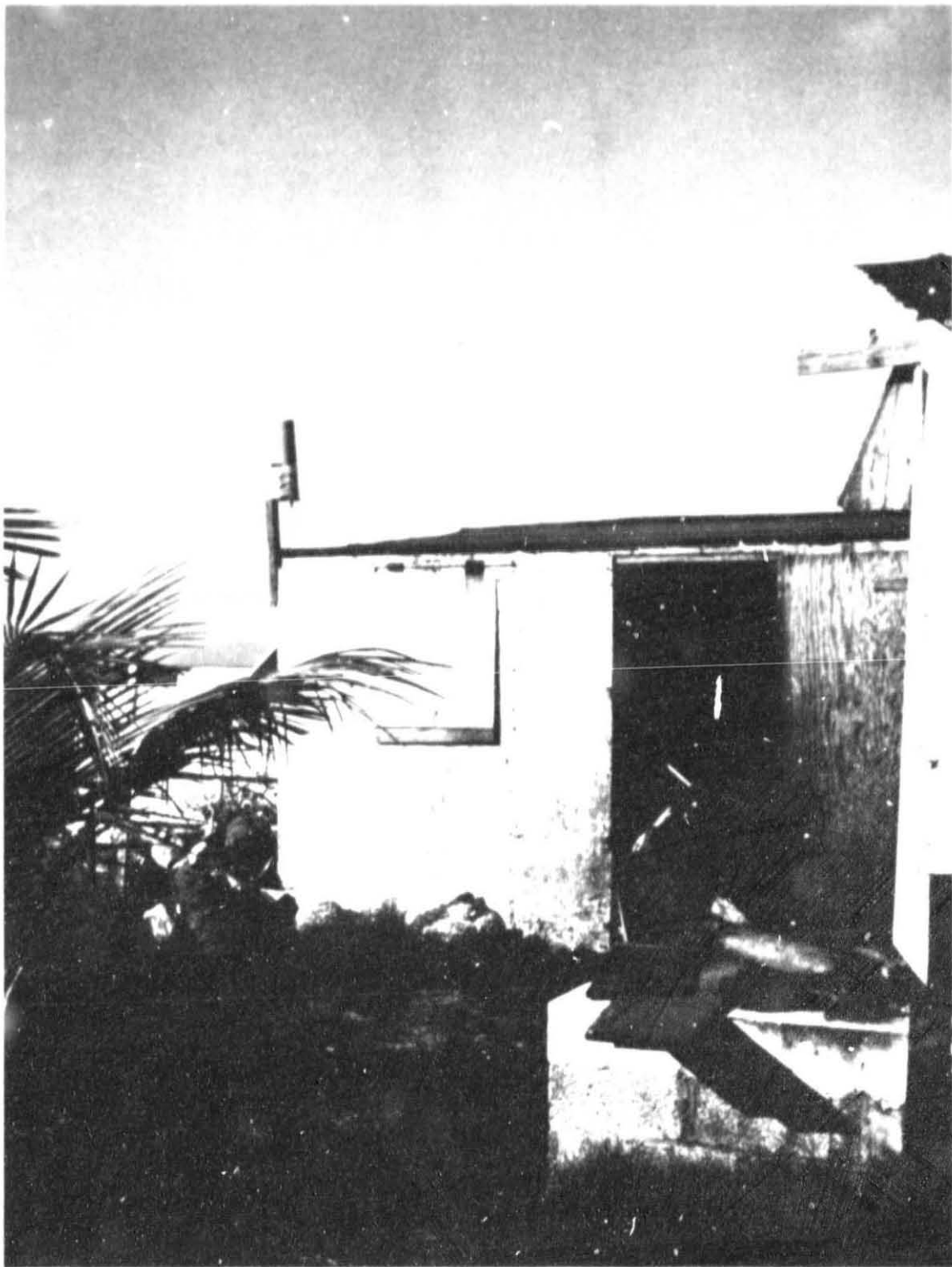


Figure 4. Anegada Tide Gauge DCP Antenna Installation

EARTHQUAKE PREDICTION

SURFACE HORIZONTAL/VERTICAL MOTION	TIDAL HEIGHTS
SURFACE TILT	WELL WATER LEVELS
MAGNETIC FIELD VARIATIONS	WELL WATER RADON
SEISMICITY	WELL WATER TURBIDITY
SUBSURFACE CONDUCTIVITY/RESISTIVITY	

VOLCANO MONITORING

SURFACE POSITION CHANGES	HEAT FLOW
GASEOUS EMANATIONS	SEISMICITY

TECTONIC FORCES AND MOTIONS

SURFACE POSITION CHANGES	SEISMICITY
STRESS MEASUREMENTS	TIDAL HEIGHTS

TSUNAMIS

SEISMICITY	TIDAL HEIGHTS
-------------------	----------------------

LANDSLIDES

PORE PRESSURE	SOIL MOISTURE CONTENT
----------------------	------------------------------

SUBSIDENCE

SURFACE POSITION CHANGES

**Figure 5. Geophysical Parameters Contributing
to Studies on Crustal Hazards**

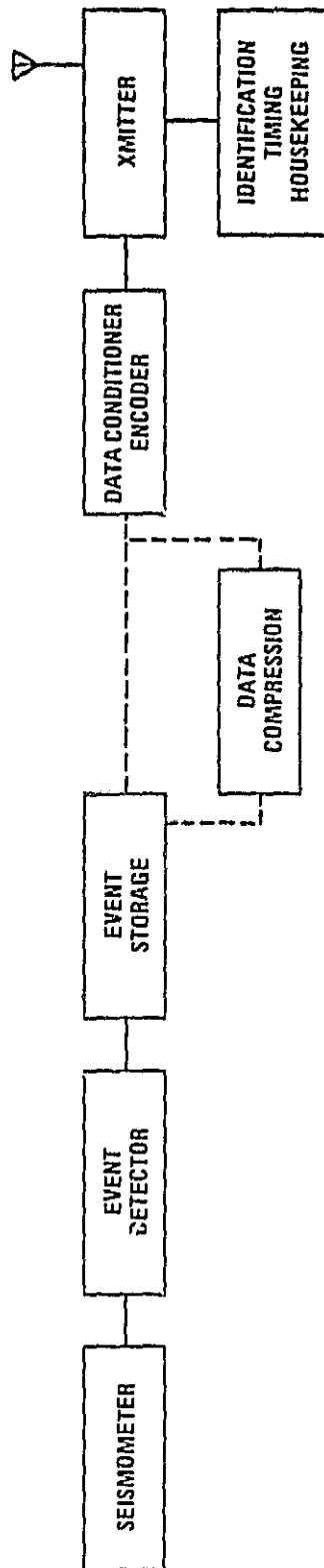


Figure 6. Block Diagram of a Seismic Data Collection Platform

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MINIMUM FEATURES PICKED	MAJOR USE
I. NUMBER OF EVENTS PER DAY	VOLCANO MONITORING
II. "P" ARRIVAL TIME DIRECTION FIRST MOTION DURATION AND/OR MAX. AMPLITUDE	LOCATION AND MAGNITUDE OF EARTHQUAKE
III. "P" ARRIVAL TIME DIRECTION FIRST MOTION DURATION AND/OR MAX. AMPLITUDE "S" ARRIVAL TIME	EARTHQUAKE PREDICTION
IV. "P" ARRIVAL TIME DIRECTION FIRST MOTION DURATION AND/OR MAX. AMPLITUDE "S" ARRIVAL TIME SURFACE WAVE FREQUENCY AND DURATION COMPLEX ARRIVAL TIMES	REGIONAL STRUCTURE STUDIES

Figure 7. Capability of Automatic Seismic Event Detection as a Function of Scientific Usefulness